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CURRENT TRENDS IN OIL DRILLING SYSTEMS R&D WITH EMPHASIS ON CROATIAN OIL DRILLING SECTOR – A REVIEW

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Abstract

A notable portion of contemporary oil drilling rigs are still equipped with mature drilling equipment such as manually-operated mechanical brake actuators for drill-string and tool weight-on-bit (WoB) and rate-of-penetration (RoP) control. Moreover, the main drilling rotary drive is usually being controlled without regard for drill-string compliance-related tool stick-slip effect, which shortens the useful life of the tool (drill-bit) and other drill-string drive mechanical components. In addition, drilling fluid pumps are typically being operated without regard for optimal pipeline pressure control. Thus, in order to meet increasingly stringent requirements on the drilling system performance, such mature drilling systems need to be retrofitted with advanced WoB/RoP and drill-string drive control systems, as well as coordinated drilling fluid pump control. Finally, the drilling process itself is extremely energy consuming, so it would also be worthwhile to analyze the operation of the drilling rig power-plant and adjacent microgrid for typical operating scenarios, in order to find appropriate measures for energy (fuel) expenditure reduction. To this end, this paper presents an overview of research and development results of such drilling automation and energy management systems, with particular emphasis on the retrofitting designs currently being researched, developed and fielded by the Croatian oil drilling-related businesses.

Keywords: drilling rig retrofitting; weight-on-bit and rate-of-penetration control; rotary electrical drive active damping speed control; stick-slip mitigation methods; mud pump pressure control; power-plant energy management control

1. INTRODUCTION

Meeting the society's energy needs, which are still being predominantly accommodated from fossil fuel sources, has become a paramount task for energy policy makers due to fluctuating crude oil prices. Even though oil price increase generally stimulates the discovery of new reserves and their enhanced recovery [1], the non-renewable nature of those resources mandate that at a certain point their peak production potential would eventually be reached [2]. Hence, numerous efforts have been undertaken by major oil/gas industries with the aim of improving the efficiency of the complete hydrocarbon production chain from exploration, through extraction and crude product transportation, and final processing and refining [3, 4].

Making use of drilling technologies advances has also been recognized as a potential factor in increasing oilfield production capacities and drilling operation cost-effectiveness [5, 6]. However, a notable portion of older oil/gas drilling rigs is still equipped with legacy mechanical hardware and electrical drive systems [7], as illustrated in Fig. 1:

(i) Manually-controlled draw-works winch mechanical brake used by the operator either alone or in combination with the hoist electrical drive to steadily descend the drill-string via a pulley-based hoisting system, thus applying weight on the rock cutting tool (drill bit) during drilling;
(ii) Rotary electrical drive implemented in the form of high-power/high-speed top-drive drilling motor equipped with a high-transmission ratio gearbox in order to produce the required large drilling torque values at relatively low drill-bit speeds (up to 150 rpm);
(iii) Drilling fluid (mud) pumps typically comprising three cylinders, each containing a piston or a plunger, driven through respective slider-crank mechanisms and a common crankshaft, and typically powered by a speed-controlled direct-current electric motor.

In particular, manual control of the top-drive hoisting system may result in inferior weight-on-bit (WoB) and tool rate-of-penetration (RoP) control performance, which would directly translate into less then desired consistency of the borehole production process [8]. Moreover, due to large lengths and small cross-sections of the drilling pipes, low tool inertia, and emphasized tool vs. rock bed friction, the rotary drill-string electrical drive is prone to poorly-damped torsional vibrations including the so-called tool stick-slip behavior [9-12]. These potentially harmful vibrations can be provoked either by the variable cutting/friction forces or the time-varying operator's commands, such as a sudden change of drill-string servomotor speed reference or variations of the WoB command, especially in the case of manual WoB control. In addition, due to each pump piston action, the pump system output flow fluctuates at a rate proportional to individual pump speed and number of cylinders. This, in turn, results in mud pressure pulsations which may adversely affect the mud pipeline components such as valves and fittings, and may also result in deteriorated performance of tool-side measurement data acquisition (so-called measurement while drilling or MWD systems) [13, 14].

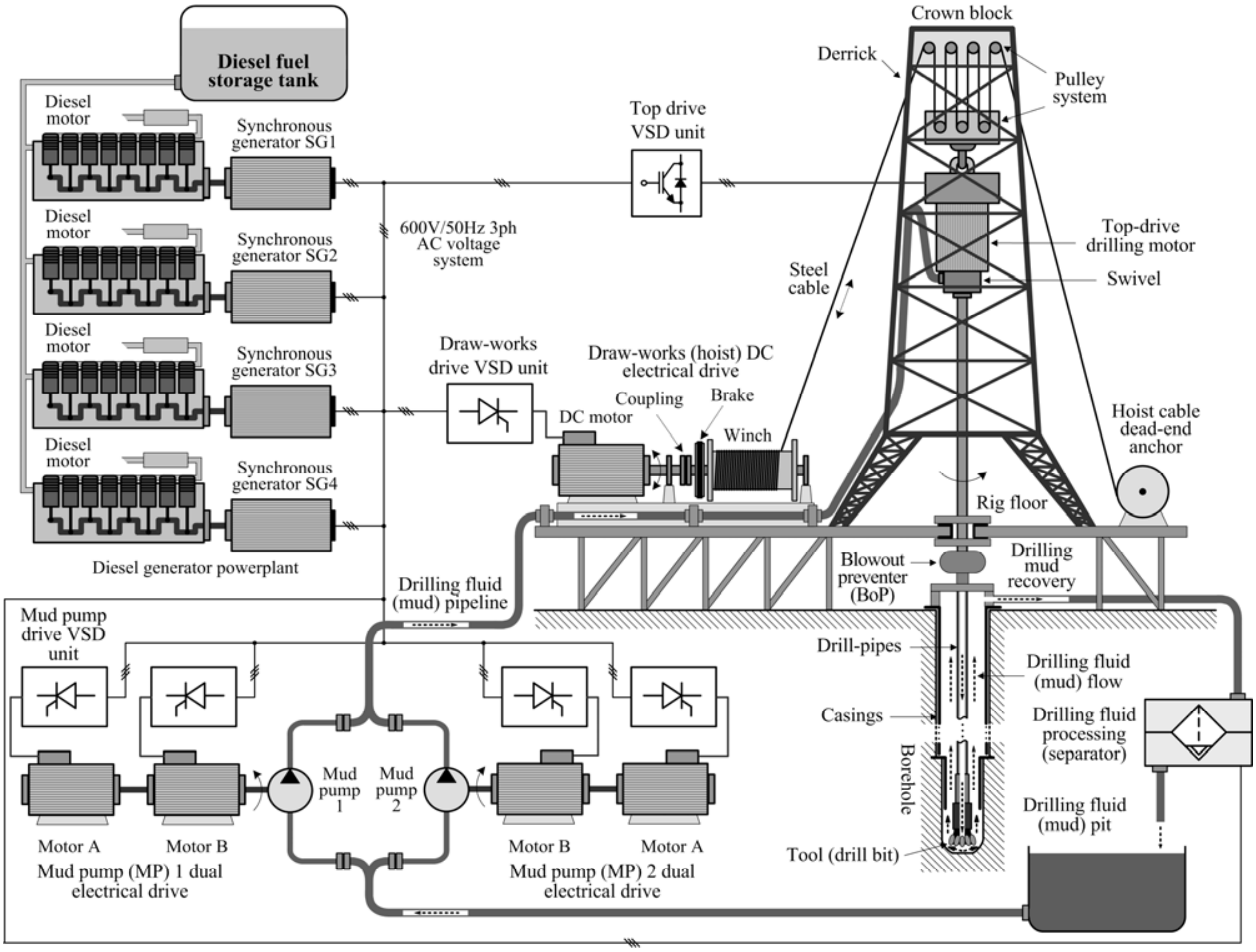


Figure 1 – Schematic layout of a typical mature land-based oil-drilling rig

In order to improve the performance of mature drilling rigs, and also to prolong their useful service life, they are typically retrofitted with more advanced draw-works winch control systems, such as those based on: (i) servopneumatic or servo-hydraulic disk brake system [8, 15]; (ii) electrical servodrive-based mechanical brake actuator [15, 16]; or (iii) utilization of the main or auxiliary draw-works electric motor [17, 18] for winch drum positioning during drilling operation, which might also be used to attenuate the stick-slip tool vibrations by means of active weight-on-bit control [19]. The drilling performance of thus refurbished rigs may be additionally enhanced by the addition of advanced drill-string rotational dynamics controls aimed at active torsional vibration suppression, which can mitigate aging and wear of drill-string drive components and further enhance the efficiency and productivity of the drilling process. Direct active damping strategies can either be realized as: (i) emulation of a passive absorber behavior [9, 20], or (ii) utilization of more advanced state-variable or robust single-loop drill-string speed controller structures [11, 12, 21-26]. Regarding the possibilities of mud pump pressure pulsations reduction, synchronization and timing of mud pump piston pump strokes has been recognized as an effective and inexpensive measure which leads to elimination of high pressure peaks due to non-synchronized pump operation [14]. Increasing the number of pistons per crankshaft revolution further reduces the pressure pulsation magnitude [13], but this would require complete replacement of the mature, but still reliable, legacy mud pump systems.

The aforementioned drilling facilities refurbishment and retrofitting actions should also be augmented at the operational (production) level by adopting appropriate energy efficiency improvement measures, such as drilling facility power-plant waste heat capture and energy storage [27], which can facilitate notable fuel savings and carbon-dioxide (CO_2) emissions reductions on off-shore drilling rigs. Since the current number of readily available land-based and off-shore drilling rigs currently numbers 925 active facilities [28], it would also be worthwhile to investigate their fuel expenditure and CO_2 emissions reduction potentials via appropriate energy management strategies. Since the aforementioned drilling control system upgrades should be far less expensive than purchasing a state-of-the-art drilling rig, their implementation would also be characterized by a much shorter return-of-investment period [29], which might make these upgrades more palatable to small and medium-size oil and gas drilling companies operating "mature" drilling equipment. This is especially true when bidding for favorable drilling contracts, wherein daily drilling rates for off-shore rigs may exceed 60 000 USD, depending on the drilling rig type [64].

To this end, this paper presents an overview of research and development (R&D) results of such drilling automation and energy management systems, with particular emphasis on the retrofitting designs currently being researched, developed and fielded by the Croatian oil drilling-related businesses. The paper is organized as follows. Section 2 presents the current state-of-the-art in drilling system automation and advanced control systems with emphasis on automatic drilling controls, torsional vibration suppression and mud pump pressure control systems, along with an outline of drilling rig energy efficiency improvement measures currently being researched. The related R&D efforts in the aforementioned areas, supported by the Croatian oil drilling sector, are outlined in Section 3. The respective control system improvement potentials have been illustrated by means of computer simulations, which are further supported by field results demonstrating the capabilities of currently developed and fielded functional prototypes of aforementioned advanced control systems. Finally, in Section 4, a novel concept of oil drilling rig power-plant fuel effectiveness improvement has been demonstrated based on an auxiliary battery energy storage system. Section 5 summarizes the main results and conclusions, and also provides guidelines for future work.

2. CURRENT STATE-OF-THE-ART IN OIL DRILLING SYSTEMS

This section presents the current state-of-the-art in advanced drilling automation systems aimed at drilling system automation in terms of precise draw-works hoist system control for the purpose of achieving WoB and RoP automatic control capabilities, torsional vibrations active damping of the speed-controlled rotary drilling electrical drive, and mud pump pressure pulsation mitigation via pump phase angle coordination. A brief overview of drilling rig energy efficiency improvement measures is also outlined herein.

2.1 Automatic drilling systems

Large variations in drill-bit RoP and WoB are likely to occur on mature drilling rigs equipped with manually controlled draw-works winch actuated during hook-load descent phase by means of a mechanical brake fitted to the winch drum, as shown in Fig. 2. This, so-called, band-brake is used by the operator to steadily descend the drill-string via a hoisting system, thus applying weight on the drill bit during drilling operations. Since variations in weight-on-bit during operation directly affect the quality and productivity of the drilling process, it is likely that relatively imprecise manual brake control would result in inconsistent quality of the drilled borehole. This, in turn, means that such rigs are less competitive compared to state-of-the-art drilling systems from the standpoint of drilling productivity and operational safety.

In order to improve the performance of older drilling rigs and thus prolong their useful service life they are typically retrofitted with automatic control systems which have been developed to simultaneously automatically control RoP and WoB via appropriate draw-works hoist system actuators (see Fig. 3). Those control systems are based on servo-pneumatic or servo-hydraulic disk brake system [8], electrical or pneumatic servo-drive based mechanical brake actuator [30-32, 36, 50], or utilization of the main or auxiliary draw-works electric motor [17, 18, 33-35]. These control systems are popularly called Auto-driller systems (*note that AutoDriller is a trade name used by Pason Co.* [31]). Each individual automatic drilling system manufacturer offers a number of features within their respective proprietary products, which include:

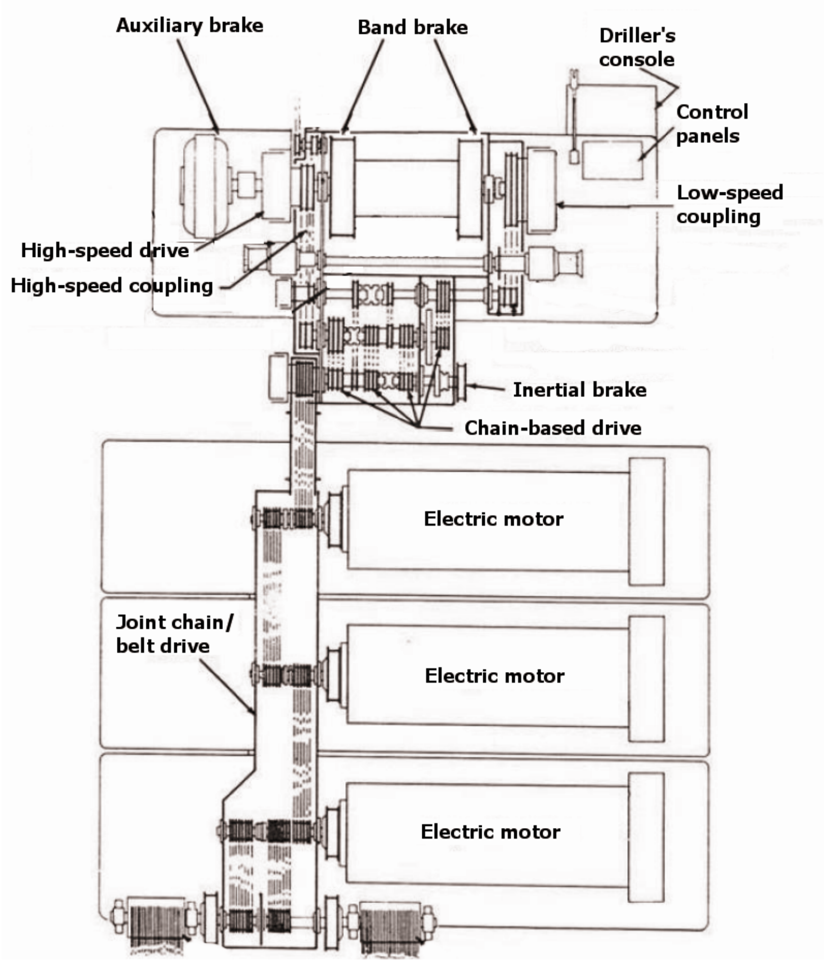
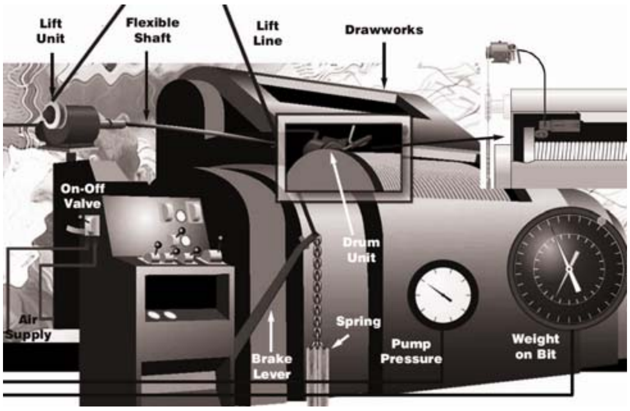


Figure 2 – Schematic layout of a typical mature draw-works hoist drive.



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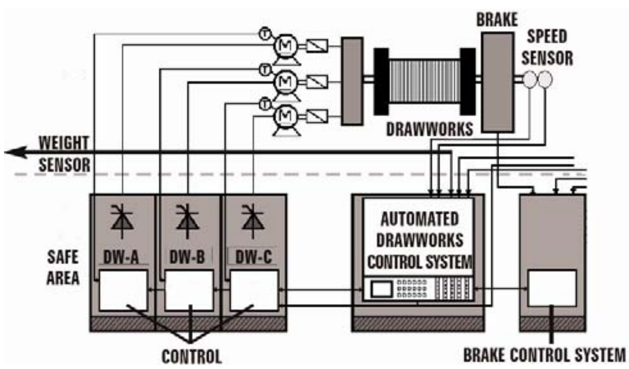


b

Figure 3 – *Wildcat^{TM}* automatic driller system by *National Oilwell Varco* [30] based on band-brake actuator (a) and *Bentec's* proposal [35] of combined brake plus draw-works motor-based automatic driller solution (b)

- WoB control with inherent RoP limiting in order to achieve consistent weight applied on the drill bit, while also assuring that high-speed drill-string descent can be prevented in the case of encountering "soft" rock formations at the bottom of the well, wherein the RoP limit is provided by the operator. A RoP control-only mode is also available on some systems (such as the one presented in [36]) irrespective of WoB command, wherein it is typically used in un-consolidated formations.
- Differential pressure (Δp) control is also available on a number of draw-works automation systems [18, 30, 31, 33], and it is normally in operation when down-hole drilling fluid-powered motor-drill is

used, such as in the case of directional drilling. Combined WoB and Δp control may also be available depending on the manufacturer [30].

- On-line adaptation to drilling process parameters [32] and mud pump system cooperative control [30] in order to improve the control system performance, and to make maximum use of down-hole drilling fluid-powered motor-drills, respectively.
- Safety features are included in all of commercially available control system packages, which typically comprise a floor-level and derrick crown saver with traveling block soft stop under speed control, band brake friction pads adjust/wear alarm and multiple emergency switches for quickly stopping the automated drilling system operation.

2.2 Torsional vibration active damping systems

The most recognizable manifestation of stationary torsional vibration is the occurrence of drill-bit stick-slip motion during rotary drilling. In particular, due to large static vs. Coulomb friction difference at the contact between the drill bit (BHA) and the well-bore coupled with the spring-like nature of the drill-string, the bit may actually stop rotating even though the drill-pipe is still being rotated at a constant rate at the surface. This is the so called “stick” phase. After a short period of stasis (standstill), sufficient torque is generated by the top-side drill-string electrical drive, which is accumulated in the drill-string torsional “spring”. This torque, being sufficiently large to overcome the tool vs. rock bed static friction, causes the drill-bit to start rotating. However, due to aforementioned large difference between static and kinetic (Coulomb) friction and the accumulated potential energy of the drill-string “spring” system, the tool accelerates to up to several times the speed of rotation conveyed by the rotary table or top-drive. This is the so-called “slip” phase.

In drilling systems equipped with “stiff” drill-string driving motor speed controllers, this phenomenon achieves the so-called limit cycle behavior, i.e. sustained high-magnitude torsional oscillations occur (Fig. 4). Namely, the aforementioned stick-slip motion results in harmonic torsional oscillations along the entire length of the drill-string, and to a lesser extent, the rotational speed at the top of the well. Stick-slip vibrations exert high cyclic stresses on the drill-pipes and slow down the drilling process, and may ultimately cause fatigue failure at the most stressed points on the drill-pipe.

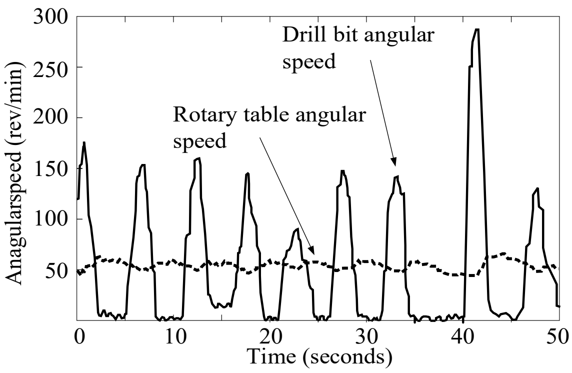


Figure 4 – Field test result from [9] revealing speed oscillations at drill-bit side

The high tool speed achieved during the slip phase may also be one of the causes of torsional drill-string vibrations, which are further exacerbated by the interaction between the rotating drill-string and the well-bore. Once initiated, these interactions are difficult to stop, and these shocks are typically not eliminated until the speed is greatly reduced, thus slowing down the drilling progress. Moreover, if bit bouncing also occurs due to combined drill-string vibrations (i.e. if axial vibrations are also present) these vibrations may also be noticeable at the surface (rig floor). Hence, torsional vibrations may cause a myriad of undesirable effects, such as cause irregular down-hole rotation that leads to fatigue of drill collar connections, damages the bit and mandates drilling progress slowdown due to the need to relieve the drill-bit downward force in order to mitigate the so-called stick-slip friction effects.

For the above reasons, many oilfield equipment manufacturers have fielded their respective active damping control systems within the rotary drilling motor control system framework [38-42], with the pioneering work having been performed by *Shell Global Solutions International*, *whose trademarked name Soft Torque*^{TM} is now-days synonymous with drill-string torsional vibrations active damping control systems [12, 20]. The original *Soft Torque Rotary System*^{TM} (*STRS*) design [20] resembles the implementation of a passive mechanical vibration absorber comprising a parallel spring-dampener connection between the stiffly-controlled drilling motor (the so-called speed source) and the drill-string, as shown in Fig. 5a. This passive absorber needs to be tuned by means of its stiffness and damping coefficients k_f and c_f in order to effectively suppress the drill-bit speed and drill-string torque oscillations due to drill-string compliance (denoted by its stiffness coefficient k_s) and bottom-hole-assembly (BHA) inertia J_{BHA}. This passive vibration absorber emulation can be conveniently represented as a proportional-integral (PI) action between the speed source (rotary drilling motor gearbox output) speed and the drill-bit speed, as shown in Fig. 5b, which can be conveniently implemented as a standard PI speed controller within the rotary drilling motor power converter. Hence, the torsional vibration active damping system implementation can be regarded as conventional PI speed controller re-tuning, wherein the controller proportional gain K_R and integral time constant T_I (referred to gearbox output) are related to passive absorber parameters as follows:

$$K_R = c_f , \tag{1}$$

$$T_I = \frac{c_f}{k_f} . \tag{2}$$

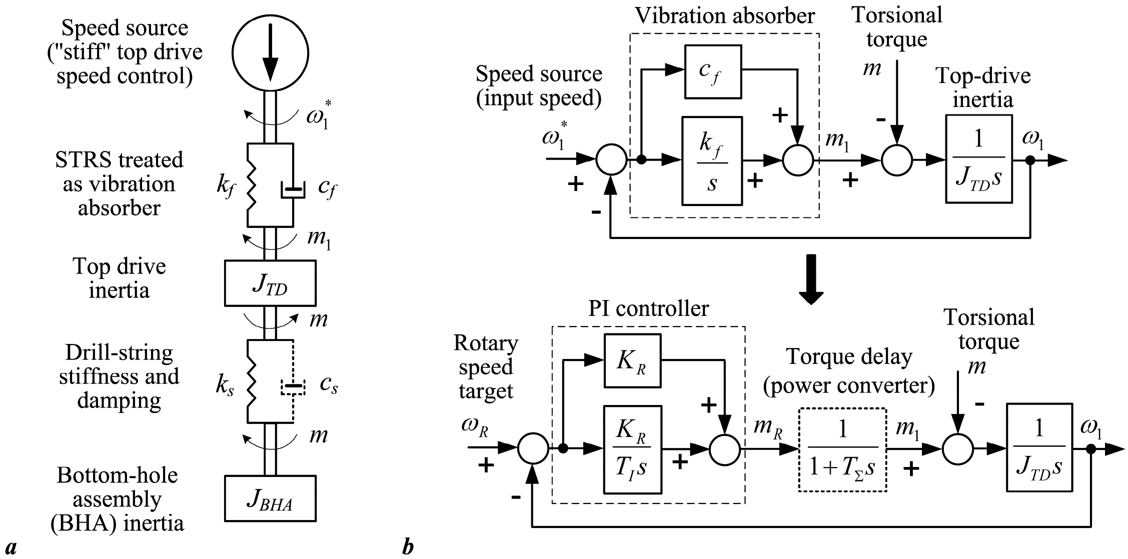


Figure 5 – Principal implementation of passive absorber-based *Soft Torque Rotary System*™ (a) and corresponding implementation within the rotary electrical drive speed control framework (b) [20]

A more recent torsional vibration active damping development [12] tries to avoid re-tuning of the rotary electrical drive PI speed controller, but rather to use the default stiff controller settings in order to establish an external torsional vibration dampening action via estimated drill-string torque. In this approach, the drill-string is treated as a waveguide for the acoustic wave propagating from the drill-bit vs. rock bed interaction side, and the so-called waveguide characteristic impedance Z is used via the drill-string torque estimate to "terminate" the line, thus preventing prolonged reflections of the shockwaves coming from the bottom-hole-assembly. Figure 6 shows the block diagram representation of such active damping system (so-called *Z-Torque*™ *system*), wherein the reference (target) of the fast rotary drive speed control loop is adjusted by the external compensation action via on-line calculated drill-string torque estimate. Since the aforementioned drill-string torque-related action affects the operator's speed target, it ought to be corrected by an additional integral action in order to facilitate steady-state speed control system accuracy.

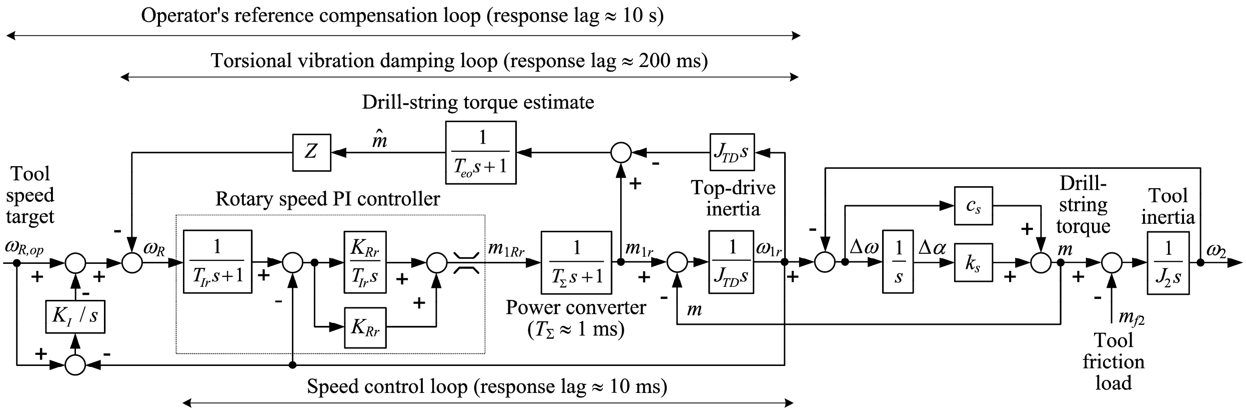


Figure 6 – Principal block diagram representation of *Shell's Z-Torque*^{TM} system [12]

Different variants of state-of-the-art active damping systems are currently available from different manufacturers under different trade names, which are given in Table 1. *Z-Torque*^{TM} system is currently being extensively tested in the field by *Shell* and their licensors [12]. In addition to torsional vibration active damping the aforementioned top-drive control systems typically feature additional functionalities such as: (i) alerting the driller when hazardous stick-slip tool operating regimes occur [39]; (ii) on-demand control system auto-tuning [39, 42, 50]; (iii) human-machine interface (HMI) [39-42, 50]; (iv) and fast data logging capability for subsequent reporting and post-processing data analysis [39-42, 50].

Table 1 – Manufacturers and trade names of state-of-the-art torsional vibration active damping systems, either based on *Shell's Soft Torque Rotary System*^{TM} concept or resulting from independent R&D.

Manufacturer	National Oilwell Varco	ElectroProject	Bentec	Canrig	HELB
Trade Name	Soft Speed II^{TM} [39]	Soft Torque^{TM} [42]	STRS^{TM} [40]	REVit^{TM} [41]	HELB - Soft Drive^{TM} [50]

2.3 Mud pump pressure pulsation control systems

During drilling operations, a drilling fluid (also called drilling mud) is circulated through the wellbore, and its main purpose is to transport cuttings from the bottom of the hole up to surface through the annulus between the borehole walls and the drill-string. Mud is also used to control the pressure in the well, in particular the mud pressure has to be higher than the well pressure in order to avoid accidental blowouts (with potentially severe consequences to personnel, equipment and environment), but also has to be sufficiently low in order to avoid accidental fracturing of the well. Mud pumps are utilized for the above purposes, and are typically realized as reciprocating piston devices, with most commonly encountered designs being triplex pumps which comprise three pistons mechanically displaced by 120 degrees (Fig. 7).

Since more than one mud pump is usually connected to the common high pressure line, high pressure peaks can occur due to asynchronous pump strokes. These may, in turn, damage the high-pressure mud lines, and pressure equipment such as valves and gaskets, and potentially undermine the wellbore stability. Typical profile of drilling fluid high pressure peaks is shown in Fig. 8a (*Soft Pump System* Off). One way of reducing these harmful high pressure spikes is by controlling the phase displacement of individual pumps with respect to each other, i.e. by synchronizing the timing of pump strokes which leads to equal peak amplitudes. For instance, if only one triplex mud pump is connected to a single high-pressure line there is no possibility of high pressure peaks since all three pistons are mechanically displaced for 120°. However, if two or more triplex pumps are connected to a single high pressure line, pressure peaks are likely to occur. This system's dynamics are chaotic, and the angular phase differential between two pumps may be considered quasi-random, and, hence, there is a much higher probability for pressure peaks to occur. The so-called *Soft Pump System*^{TM} offered by *Bentec* controls the pump motors in such a way that their angular phase differential is kept at its optimum value, so that high peaks do not occur, as illustrated in Fig. 8b (*Soft Pump System* On). As an added benefit, the resulting quasi-continuous mud flow control with low-peak pressure magnitude enables the filtration of mud pressure pulsation signals from the Measurement While Drilling (MWD) or Logging While Drilling (LWD) tools.

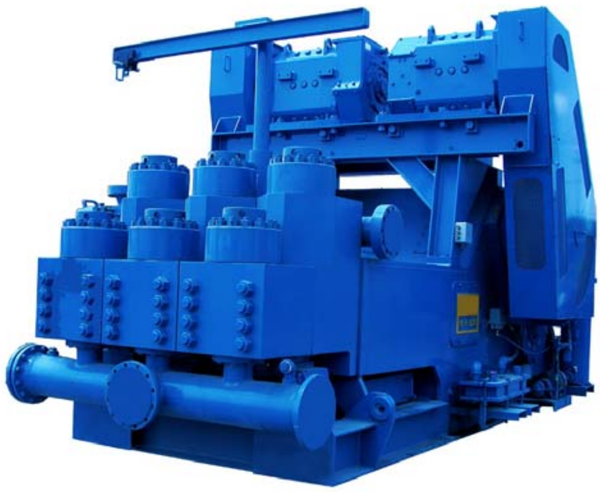


Figure 7 – A three-piston (triplex) mud pump system [43]

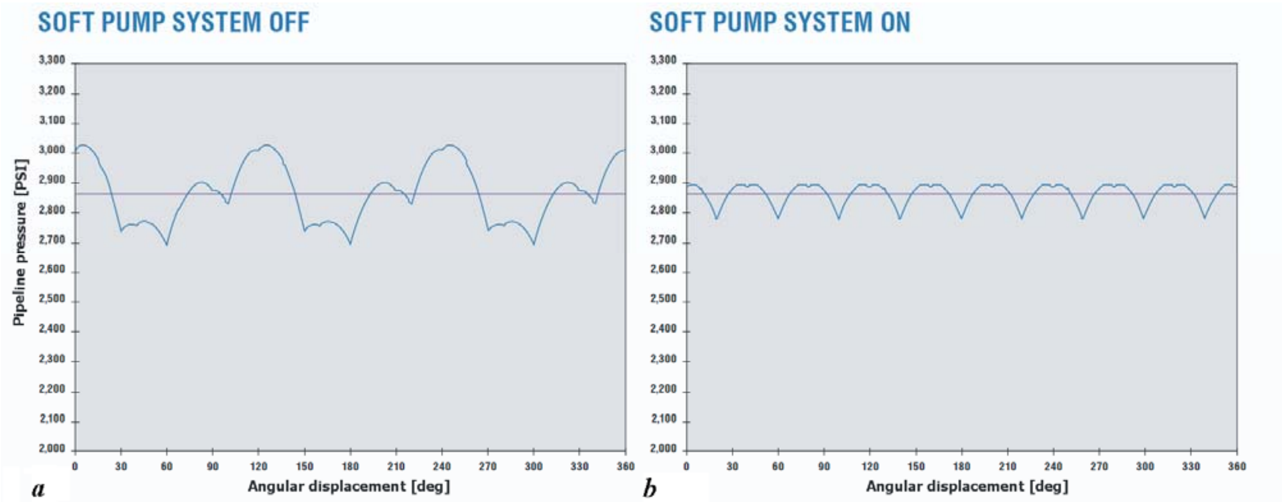


Figure 8 – Mud pipeline pressure pulsations without (a) and with (b) *Bentec's Soft Pump System*^{TM} [44]

2.4 Drilling rig energy efficiency improvement measures

Even though there has been relatively little discussion in the available literature regarding the energy efficiency improvement measures related to oil drilling facilities and operational equipment, these measures have started to appeal to oil/gas drilling and supporting enterprises. One such example is the innovative diesel engine + fuel cell off-shore platform supply vessel design with clear fuel efficiency improvement potential [45]. Moreover, off-shore drilling facility power grid reliability and efficiency improvement through adopting hybrid AC/DC distribution systems have been analyzed in [46]. In that regard, on-shore drilling rigs retrofitting with active power filters has been researched in [47] aimed at improving the grid power quality and reducing grid harmonics-related power losses. Additional efforts related to drilling operations efficiency improvement may also include harnessing the regenerative braking operation of the draw-works hoist drive during drill-string descending phase [48], whereas reference [49] discusses energy efficiency improvement measures related to the off-shore drilling facility power-plant waste heat capture and energy storage, showing notable fuel savings and carbon-dioxide (CO_2) emissions reduction potentials.

3. CROATIAN OIL DRILLING R&D EFFORTS AND COMMERCIAL PRODUCTS

3.1 HELB Automatic Drilling Systems R&D

The commercially available automatic drilling system developed as a cooperative effort of *HELB Ltd.* and University of Zagreb (so-called *HELB Automatic Drilling System* or *HELB - Automatic Driller*^{TM} [50]) is based on a position-controller servomotor coupled to the band-brake lever actuator via a steel rope and a pulley system, and also equipped with a lever actuator return spring, which act as a preloading device and a safety measure (Fig. 9a). The simplified block diagram representation of the automatic drilling control system is shown in Fig. 9b, wherein the automatic drilling system is conveniently arranged in the so-called cascade control system structure (see e.g. [51]). In the particular arrangement, the outermost WoB controller commands the reference to the RoP control system based on the WoB target commanded by the operator and the actual WoB value provided by the hook-load/WoB sensor. In order to prevent high-speed drill-string descent in the case of drill-bit encountering "soft" rock formations, the RoP reference can be explicitly limited by the operator. The inner RoP controller utilizes precise drum position measurements from a heavy-duty high-precision incremental encoder [52], and commands the reference to the innermost servomotor positioning control system. In order to ensure the fully-active electrical drive operation, the lever mechanism is equipped with the aforementioned preloaded return spring.

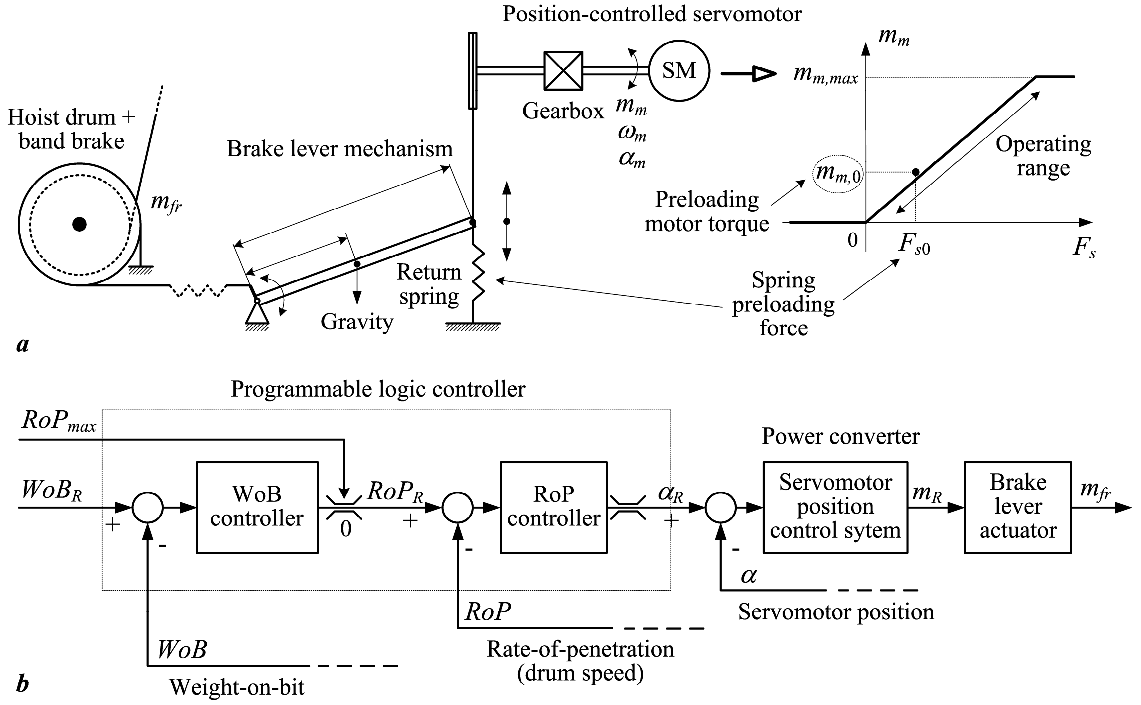


Figure 9 – Simplified representation of brake lever servomechanism (a) and block diagram representation of *HELB - Automatic Driller*^{TM} cascade control system arrangement (b)

The performance of *HELB - Automatic Driller*^{TM} has been validated in several field implementations. Its effectiveness is illustrated by long-run data shown in Fig. 10. These results indicate that the proposed automatic driller system facilitates more effective suppression of WoB perturbations compared to manual drilling, and, in turn, results in steadier penetration with less RoP variations.

However, the brake based automatic drilling system operation is inherently limited by the nature of brake-based draw-works hoist actuator, which only facilitates drill-string descending (a semi-active system can only be considered in that case). As shown in the relevant literature review above, many manufacturers of automatic drilling system retrofitting packages propose to either utilize the main draw-works electric motor [33] or auxiliary electric motors coupled to the draw-works winch via a high-ratio transmission system [34]. The idea to use the main draw-works motor has been intensively researched in cooperation with Croatian oil drilling sector, with the electrical drive-based automatic driller mechanical system model shown in Fig. 11, which is used as a basis for the development of accurate automatic drilling system simulation model, as well as WoB/RoP control system design.

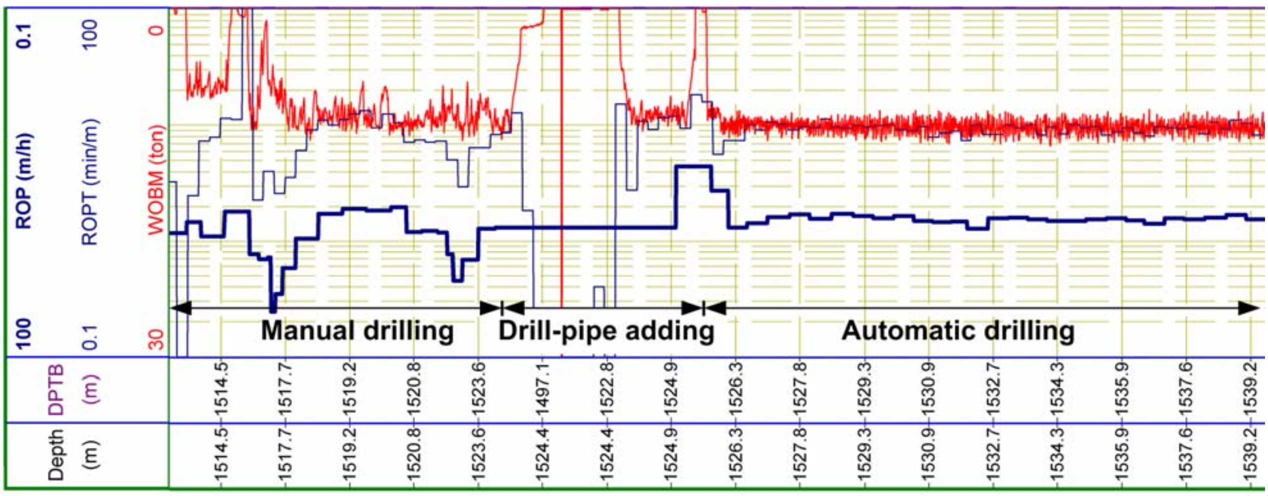


Figure 10 – Results of long-run recording of WoB and RoP data by on-site geological service

Figure 12 shows the principal block diagram of the WoB control system based on WoB proportional-integral (PI) controller receiving WoB measurement from the simple hook-load model augmented with WoB measurement low-pass filtering in order to remove the noise from the WoB signal. WoB controller also features the sign reversal which relates to the increase of WoB when descending speed command is issued to the inner RoP (winch motor speed) controller. In the above automatic drilling system arrangement, it is assumed that the draw-works winch servomotor speed control loop is tuned for a fast response, i.e. fast PI speed controller is implemented within the servomotor power converter.

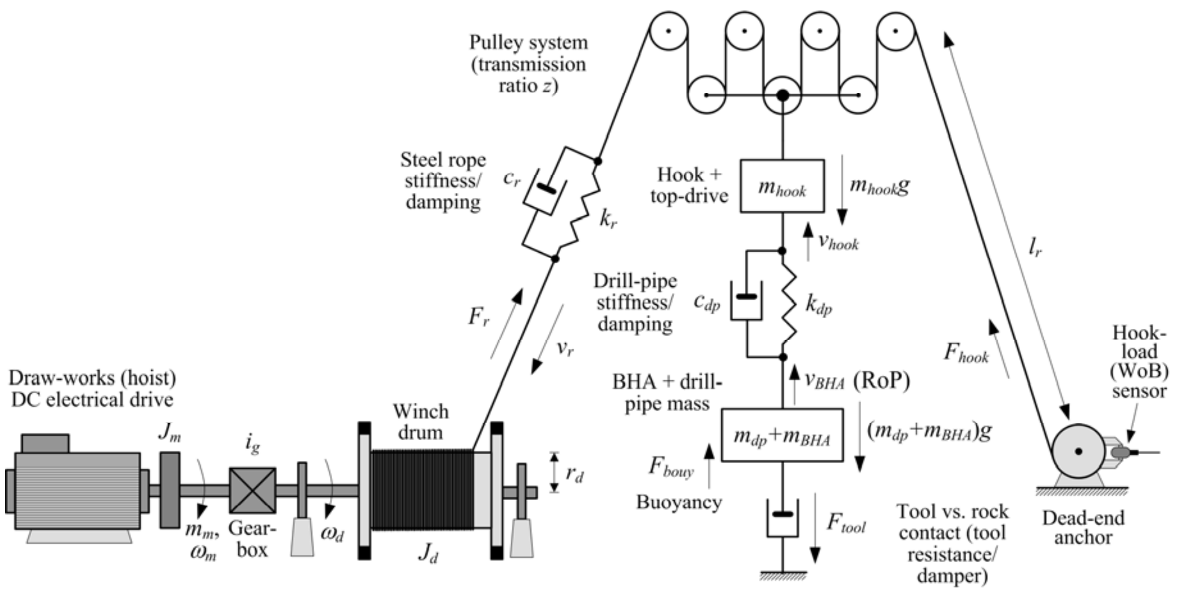


Figure 11 – Principal schematic representation of drill-string draw-works electrical drive

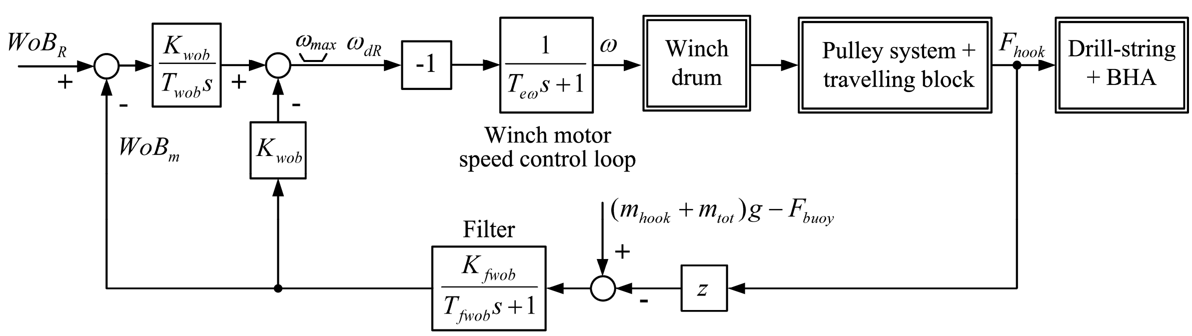
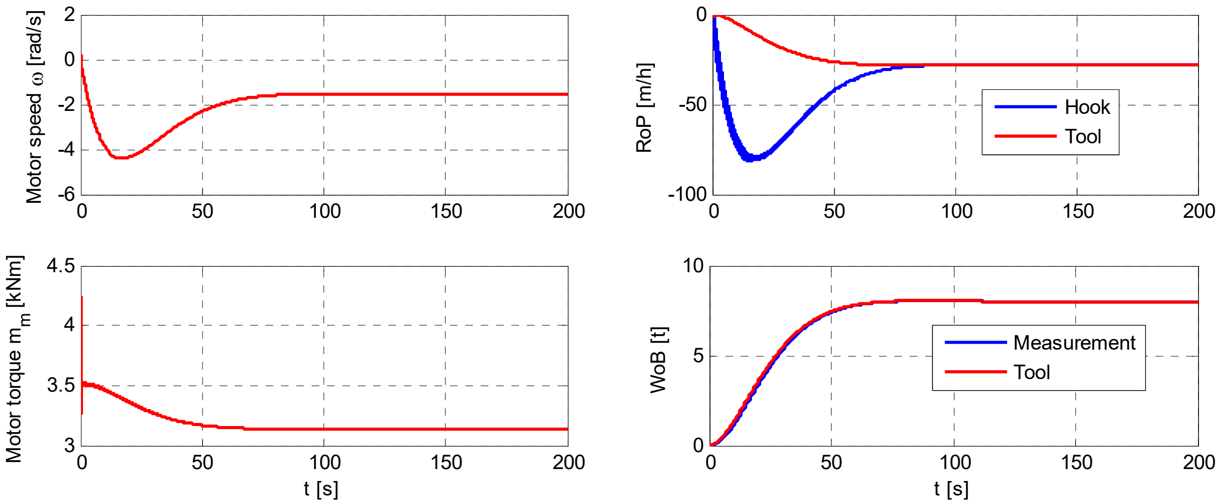


Figure 12 – Block diagram of automatic drilling system weight-on-bit control loop based on draw-works electrical drive fast inner speed control loop

The preliminary simulation results of the electrical drive-based automatic drilling system, obtained within *Matlab/Simulink*^{TM} framework, are shown in Fig. 13. These results are encouraging in terms of favorable WoB response speed and control system steady-state accuracy. In particular, the proposed WoB controller commands the winch drive to initially accelerate the hook load downwards in order to develop the requested weight-on-bit (WoB), which, in turn, requires compressing the drill-string in the longitudinal direction during the WoB transient phase. Once the stationary WoB of is achieved, constant RoP is maintained by the winch drive under the constant-valued RoP command from the WoB controller.



a ***b***

Figure 13 – Draw-works motor (a) and drill-string system (b) simulation responses (WoB_R = 8 t)

3.2 HELB Active Damping System – Soft Drive

The commercially-available *HELB Active Damping System - Soft Drive*^{TM}) has also been developed in cooperation between *HELB Ltd.* and the University of Zagreb [53]. It is based on a well-established proportional-integral (PI) speed controller of rotary drilling electrical drive (top-drive), extended with operator's speed reference and torque limit bypassing and modification scheme (see Fig. 14), aimed at avoiding the potentially hazardous back-spinning motion, which may occur when the tool becomes stuck at the bottom of the well (see [11]).

The PI speed controller tuning rules are based on the so-called damping optimum criterion [51], which aims to achieve the so-called quasi-aperiodic closed-loop response with small (typically 4-8%) step response overshoot. For this so-called "optimal" case, the expressions for controller parameters are given in their following final forms:

$$T_I = \frac{2\sqrt{2}}{\Omega_{02}}, \tag{3}$$

$$K_R = \frac{2\sqrt{2}}{3}\Omega_{02}(J_1 + J_2 / i^2), \tag{4}$$

where J_1 is the motor-side inertia, J_2/i^2 tool-side inertia referred to the motor shaft (i is motor gearbox transmission ratio), and Ω_{02} is the natural frequency of tool vibrations (which would occur when the motor is stiffly controlled), given as follows:

$$\Omega_{02} = \sqrt{\frac{k_s}{J_2}}. \tag{5}$$

Note that the active damping PI controller parameters are adjusted with respect to the value of the tool free vibrations resonant frequency Ω_{02}, which facilitates favorable torsional vibration damping by means of control, in contrast to traditional ("stiff") PI controller tuning which neglects the drill-string torsional compliance and results, which typically results in emphasized tool-side speed oscillations [9, 11, 51, 54].

The active damping control strategy extension for the prevention of back-spinning effect [11] comprises a flip-flop logic (Fig. 14) which detects if the tool is stuck, i.e. if motor speed ω_1 significantly differs from the model-based prediction) while a large torque demand m_{1R} is commanded to the motor (close to the operator's torque limit $M_{max,op}$). In that case, the flip-flop is set (Q = 1), and the speed reference is temporarily switched to a small negative value $\omega_{R,NEG} < 0$ in order to unwind the drill-string in a controllable way. The speed reference ω_R is returned to the operator's reference $\omega_{R,op}$ (the flip-flop is reset, Q = 0) when the drill-string is sufficiently unwound (m_{1R} is relatively small), and if operator commands a zero speed reference.

Since stuck tool conditions correspond to constrained electrical drive motion, an additional torque reserve should be ensured in order to safely unwind the drill string during drive deceleration transient [11]. This torque reserve is related to motor momentum under constrained motion conditions $J_1\omega_{1s}$ and the natural frequency of motor vibrations Ω_{01} (e.g. when the tool is stuck):

$$\Omega_{01} = \sqrt{\frac{k_s}{J_1 i^2}} \ . \tag{6}$$

The constrained motion motor speed ω_{1s} is available from the simplified drive first-order dynamic model (Fig. 14), characterized by the gain parameter (reference scaling parameter) K_c:

$$\omega_{1s}(s) = \frac{K_c}{1 + K_c T_I s}\omega_R(s) \ , \quad K_c = \frac{K_R}{K_R + J_1 \Omega_{01}^2 T_I} \ . \tag{7}$$

The effectiveness of the proposed active damping strategy has been tested on a commercial drilling rig. For the purpose of benchmarking, the active-damping PI controller has been compared with the default ("stiff") drill-string motor controller.

Figure 15a shows the comparative test results for the case of drilling with the stepwise WoB change from 6 tons to 8 tons, wherein the active damping controller is able to suppress the torsional vibrations much better compared to the default controller. The performance of the aforementioned controllers is compared based on the 48 hours monitoring of drilling torque and WoB by the on-site geological service, as shown in Fig. 15b. The torque response indicates that the application of active damping controller results in much smoother drill-string operation compared to the default controller (the RMS value of drilling torque perturbations is reduced by more than 50%). Moreover, this performance improvement is obtained for the approximately 15% increase of the average WoB, thereby also improving the drill-string rate of penetration.

Figure 16a shows the drill-string drive control field results when back-spinning phenomenon occurs. Due to stuck tool the motor torque, being slowly ramped up, ultimately reaches the upper torque limit for motoring operation, and it consequently starts to slow down until all of the motor momentum is spent to further build up the drill-string torque. This torque difference accelerates the drive in the opposite direction, wherein the motor power converter switches to the braking mode. Since the braking torque is limited due to quite small braking power limit, a sudden increase of motor deceleration occurs, thus resulting in high peak values of negative motor speed (back-spinning interval). On the other hand, when back-spinning prevention algorithm is turned on (Fig. 16b), operator's speed reference is switched to a small negative internal speed reference (see Fig. 14), which results in a controlled and safe drill string unwinding process.

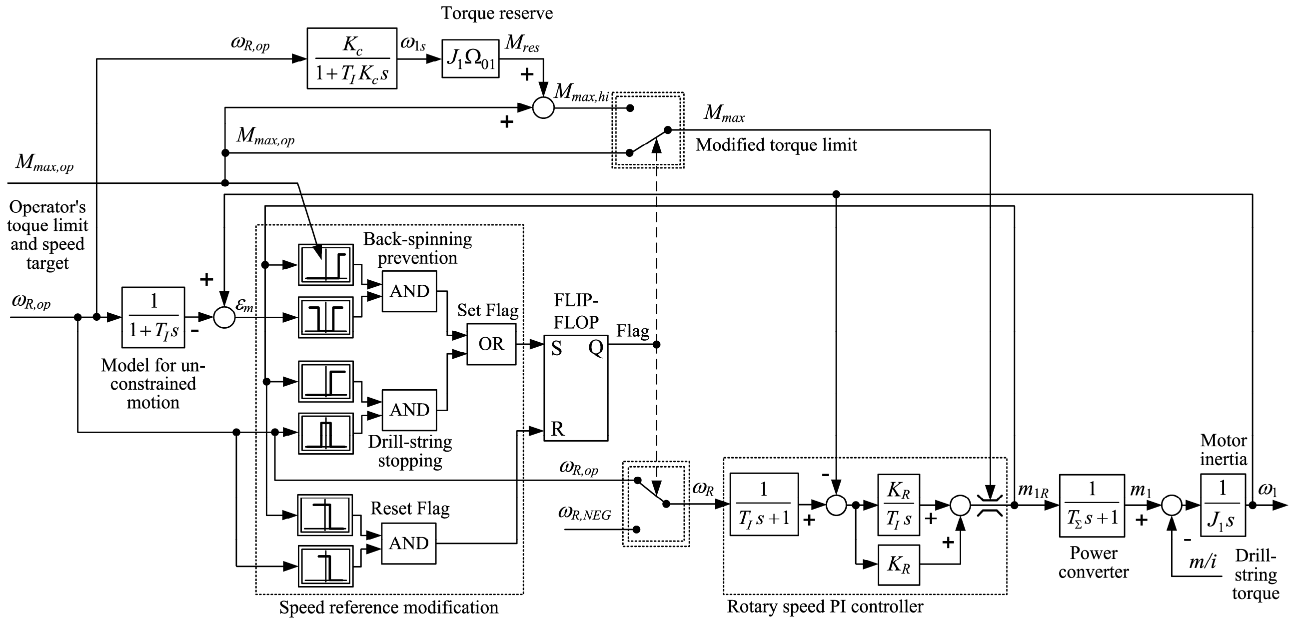


Figure 14 – Simplified block-diagram representation of *HELB Active Damping System – Soft Drive*[TM]

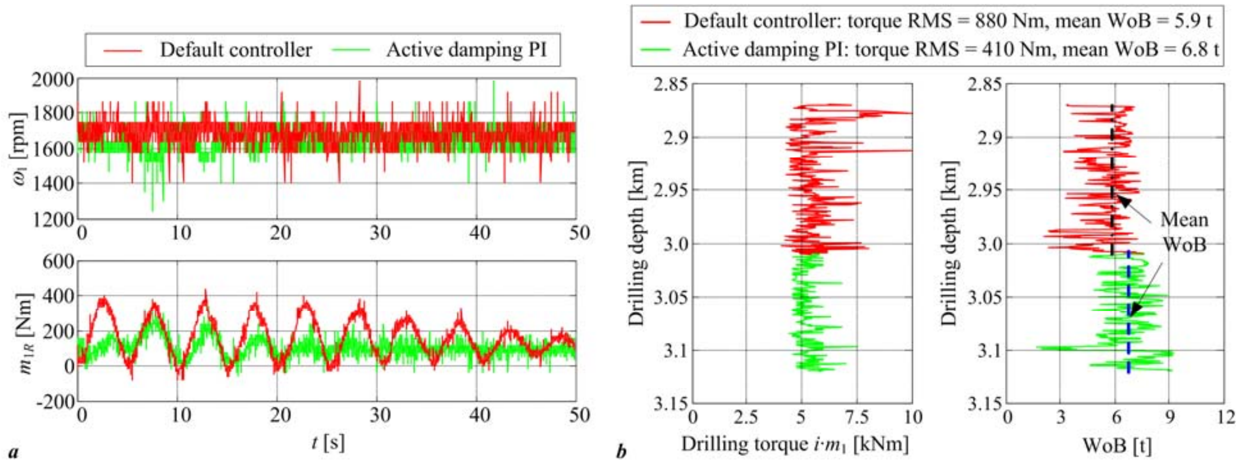


Figure 15 – Comparative traces of default ("stiff") and active damping PI controller for sudden WoB increase (a) and their performance comparison in terms of torque variation RMS value (b) in the field

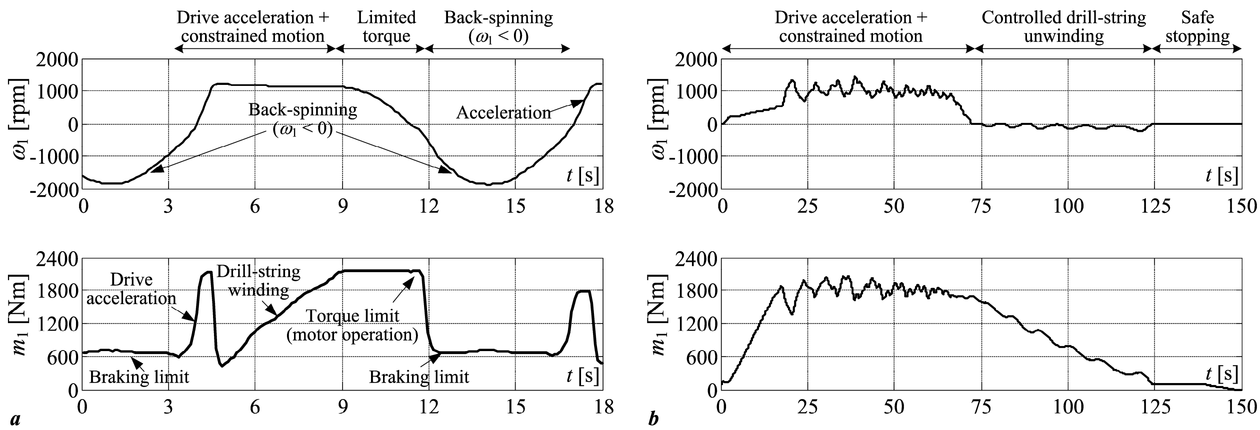


Figure 16 – Field results of drill-string drive control without (a) and with back-spinning prevention (b) when drill-string or bottom-hole-assembly becomes stuck within the well-bore

3.3 Overview of current Mud Pump Coordinated Control research efforts

A drilling fluid (mud) pump is a positive displacement machine comprising typically three cylinders and pistons being driven through respective slider-crank mechanisms and a common crankshaft powered by an external power source such as speed-controlled electric motor. Figure 17 shows the simplified hydraulic circuit of the drilling fluid and the mechanical part of the mud pump mechanism. Three pump cylinders are mechanically coupled by a crank shaft (each separated by a $360°/n = 120°$ degree angle). Electric motor(s) propel their respective crankshafts through power transmission chain and gearbox. The pump capacity is governed by the rotational speed of the crankshaft, and the number of pistons and their respective dimensions. Unlike a centrifugal pump, a positive displacement pump does not develop pressure, it only produces a flow of fluid. The downstream piping system produces a resistance to this flow, thereby generating pressure drop within the piping system [55]. Since pump flow fluctuates at a rate proportional to the pump speed and the number of cylinders, the amplitude of these flow fluctuations and resulting pressure pulsations is a function of the number of cylinders.

Based on the schematic representation of single pump system in Fig. 17, a simulation model of the triplex mud pump has been built, as illustrated by the block diagram in Fig. 18, which also includes a speed-controlled DC electrical drive. This single pump model has been used to build a more comprehensive multiple mud pump system simulation model, which is used in the research and development of mud pump coordinated control system aimed at minimizing the hydraulic pressure pulsations.

Figures 19 and 20 show comparative responses of mud pump system pressure without and with individual pump phase coordination controls, wherein simulation models have been implemented within *Matlab/ Simulink*^{TM} software environment. In the case when uncoordinated pump operation is considered at constant and identical rotational speed (Fig. 19), quite oscillatory drill string pressure response can be obtained. From Fig. 19 it is also evident that smaller pulsation magnitudes (and higher pulsation frequencies) may be obtained in the case when three pumps are connected together to the common pipeline. By introducing a phase (angular displacement) coordination between individual pumps for two and three pumps connected to the pipeline (Fig. 20), pressure pulsations are notably suppressed compared to case of uncoordinated pump operation, with expected lower level of pulsations achieved for the case of three pumps.

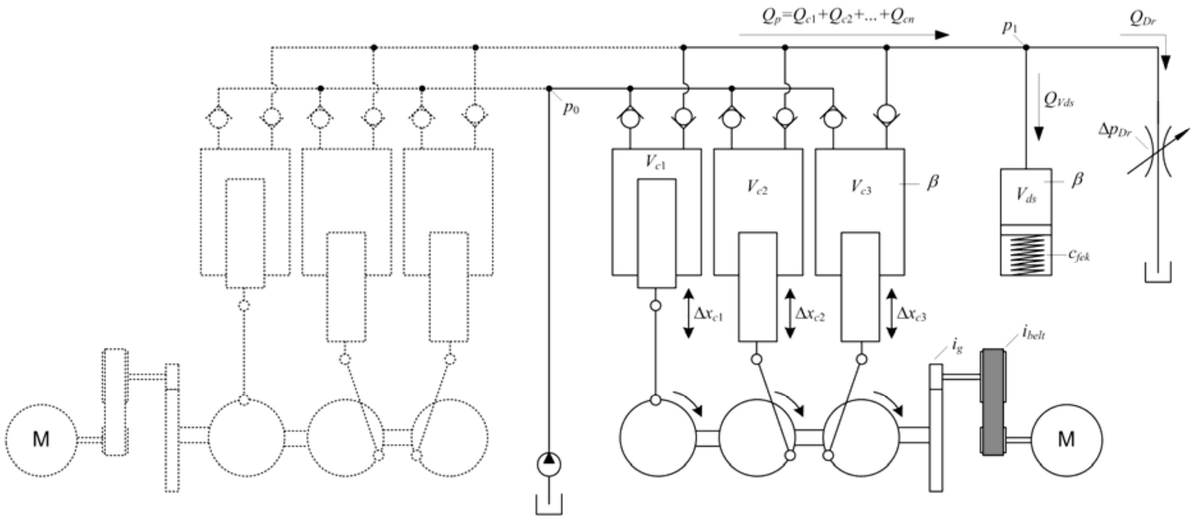


Figure 17 – Principal schematic representation of simplified mud (drilling fluid) hydraulic cycle

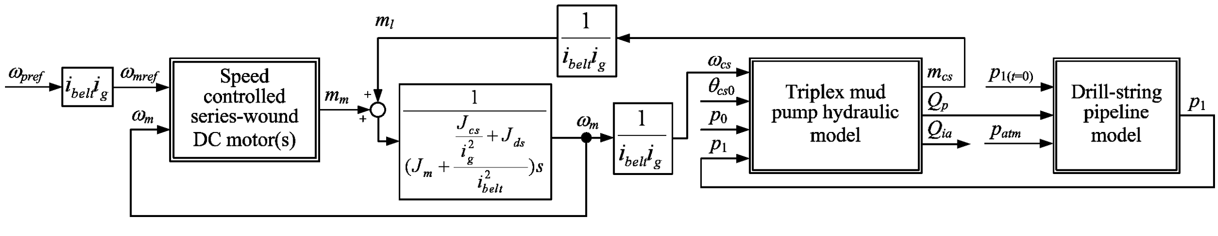


Figure 18 – Principal block diagram representation of overall triplex mud pump model

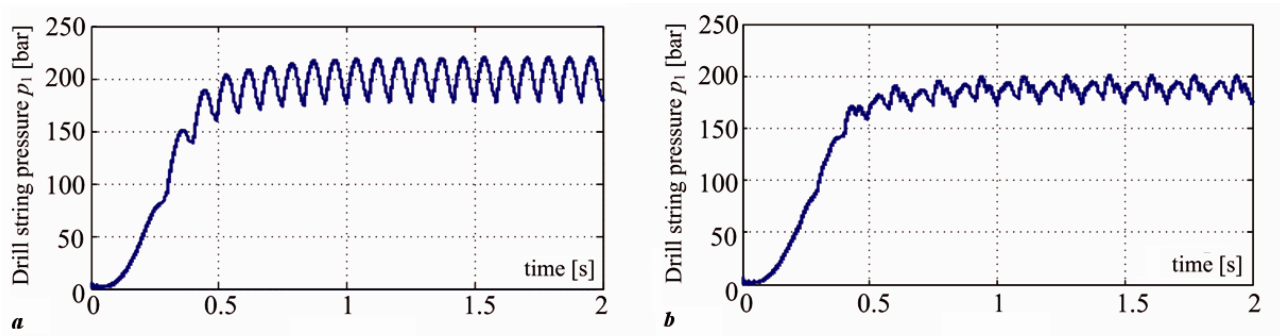


Figure 19 – Simulation model pressure responses of overall triplex mud pump system for two uncoordinated pumps (a) and three uncoordinated pumps (b) showing notable pipeline pressure pulsations

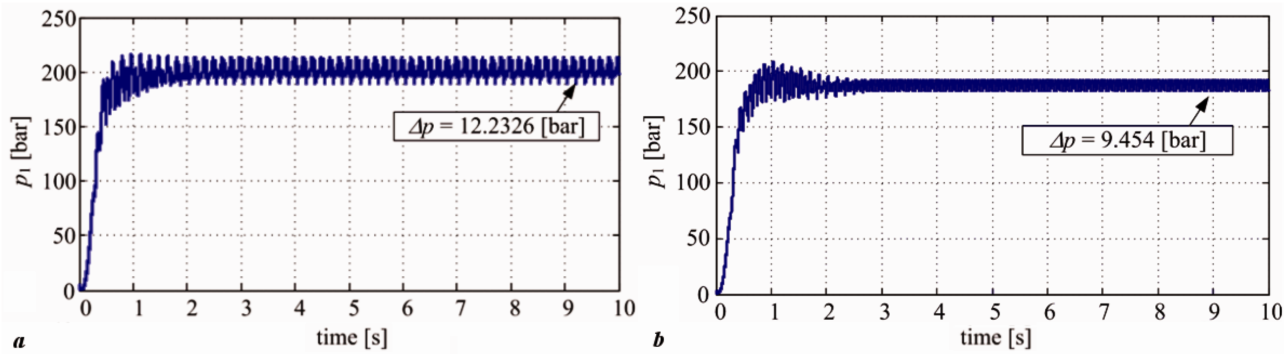


Figure 20 – Simulation model pressure responses of overall triplex mud pump system for two pumps (a) and three pumps (b) when individual pump phase angles are coordinated

4. ENERGY MANAGEMENT SYSTEM R&D

In order to investigate the potentials for fuel expenditure reduction of isolated oil drilling rig diesel power-plant, a data set corresponding to 30 days of drilling rig AC microgrid operation has been collected on an on-shore oil drilling rig [56]. The overall power-plant power flow data, shown in Fig. 21, indicate that the drilling rig AC microgrid is characterized by highly-variable active and reactive load profiles due to intermittent engagements and disengagements of high-power electric machinery such as top-drive, draw-works and mud-pump motors. The analysis in [56] has shown that:

(i) Low-power operation of individual generators needs to be avoided due to lower generator fuel efficiency in that case;

(ii) By providing peak power requirements (peak shaving) from a dedicated energy storage system, the power-plant fuel consumption may be notably reduced.

The theoretical result for the minimum number of operating generators is shown in bottom right plot in Fig. 21, wherein the averaged apparent power of individual generators (S_N = 875 kVA rated power) operating at nominal power factor ($\cos\varphi = 0.8$) has been used as the criterion for bringing additional generators on line, whereas load peaks are assumed to be covered by sufficiently sized energy storage system. This result clearly indicates that it would be possible to operate the drilling rig microgrid with a reduced number of generators and with similar number of generator switch-on/switch-off events (around 30) when compared to the current practice in the field, wherein individual generators are frequently operated at the fraction of their nominal power. By reducing the number of generators the useful generator power range would be better utilized, as illustrated by the individual generator fuel-consumption curves in Fig. 22 (see [57]).

In order to account for peak power demands, a suitably fast auxiliary energy storage system needs to be employed and coordinated with the main power supply [58] (diesel power-plant in this case). The considered drilling rig AC microgrid can be hybridized by using an appropriate battery energy storage system (BESS) equipped with grid-side power converter (grid inverter) topology [59], as shown in Fig. 23.

Since electrochemical batteries are considered for energy storage, deep discharges should be avoided in order to prolong the battery energy storage system useful cycle life, which is typically inversely proportional to the average depth-of-discharge during battery calendar life [60]. Due to specific requirements of land-based drilling rigs, the energy storage system ought to be robust, compact and easily transportable, and characterized by inherently high operational safety. The lithium-iron-phosphate ($LiFePO_4$) battery technology currently represents a promising choice in terms of high power density and operational safety, while also being characterized by relatively moderate costs with respect to energy storage capacity [61]. Moreover, these batteries are also characterized by rather high durability in terms of battery cycle life as reported in [62], and are also characterized by low resistive power losses [63].

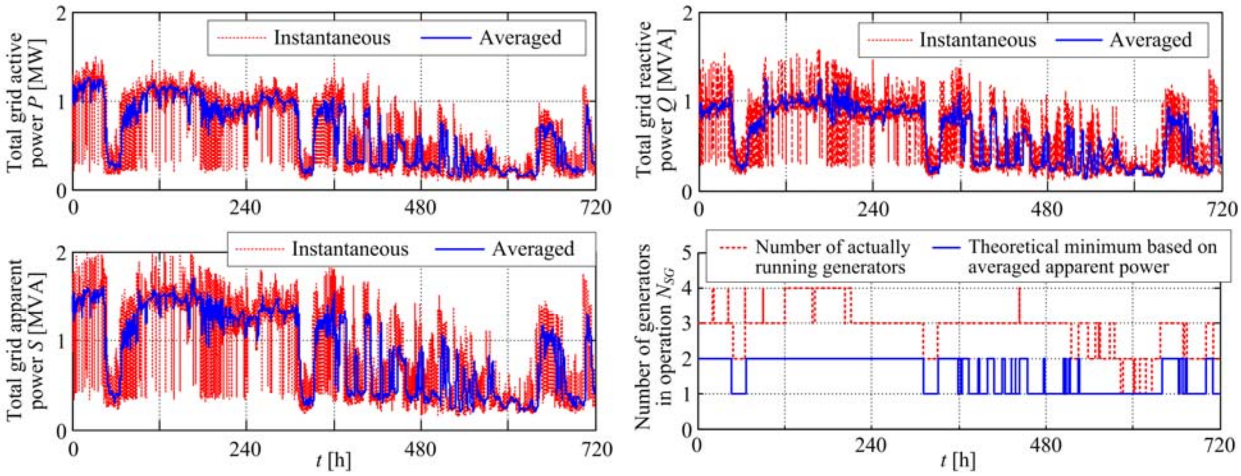


Figure 21 – Instantaneous and averaged power-plant output and number of running generators over 30 days, along with theoretical number of generators if “ideal” energy storage system is used

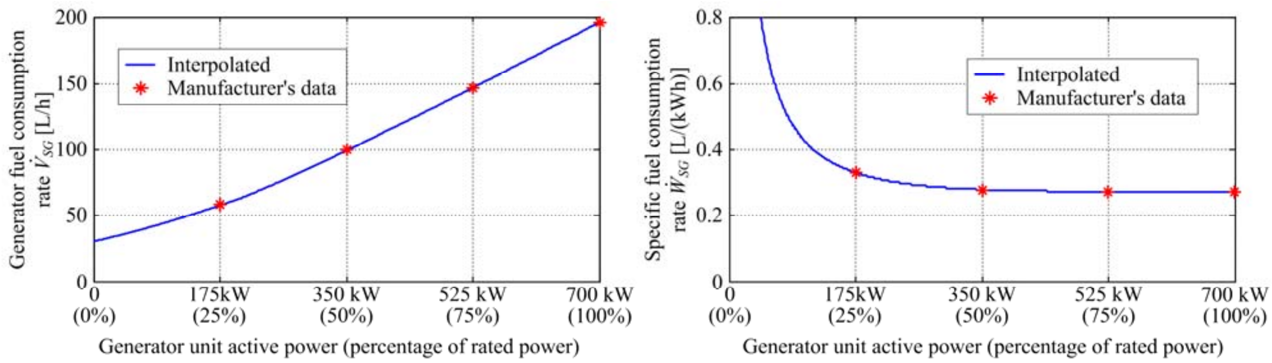


Figure 22 – Diesel generator fuel consumption rate data obtained from [57], with cubic polynomial-based approximation curve suitable for fuel consumption estimation

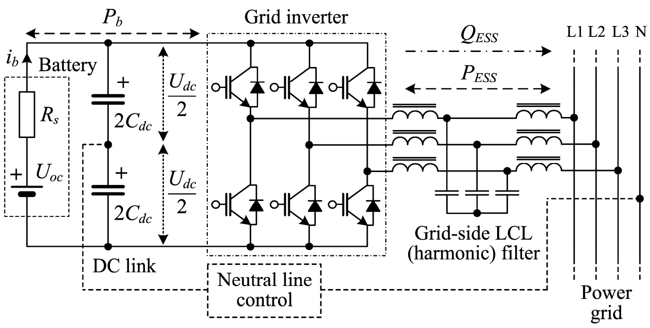


Figure 23 – Principal schematic of grid-connected battery-based energy storage system (BESS)

Figure 24 shows the results of the drilling rig hybrid AC microgrid simulation model implemented within *Matlab/Simulink*^{TM} environment [56]. For the particular scenario in Fig. 24, the grid inverter needs to supply up to 0.6 MVA, with grid active power delivery from the battery reaching up to 0.4 MW (top left plot in Fig. 24), with 78 generator turn-on/turn-off switching events (top right plot in Fig. 21), which is roughly 2.6 times more than in the “ideal” (load preview) case analyzed in Fig. 21. This increase in generator requirements is primarily due to additional requests for battery recharging when low state-of-charge is detected and realistic energy storage system losses. Finally, the power-plant estimated fuel consumption is compared to the result obtained from generator field data (bottom plots in Fig. 24), which indicates there is a clear potential for fuel consumption reduction. Namely, fuel savings with respect to power-plant operation in the field are estimated to ΔV_F = 17.69 m^3 over the observed 30-day period. This corresponds to 12% estimated fuel efficiency improvement for the particular simulation scenario considering hybridized AC microgrid equipped with BESS. Based on the aforementioned fuel savings estimates, a notable CO_2 emissions reduction potential has also been identified in [56], along with estimated BESS return-of-investment period of less than two years (less than 20% of the anticipated BESS calendar life).

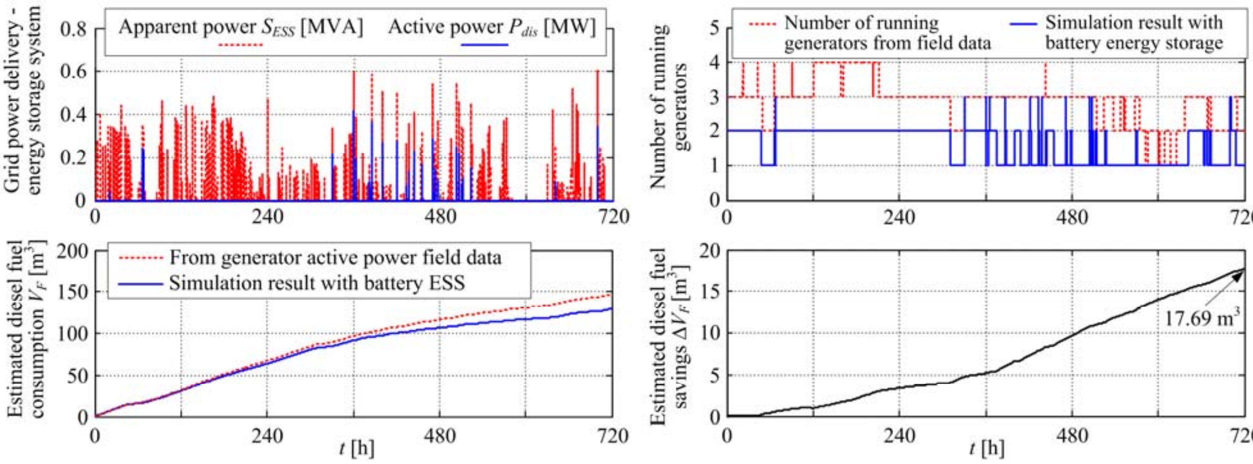


Figure 24 – Energy storage system power delivery, comparative number of power-plant running generators, and estimated fuel consumption reduction potentials

5. CONCLUSION

The paper has presented an overview of research and development and currently available state-of-the-art technological solutions for oil drilling rig automation purposes, supplied by established manufacturers such as *Shell*, *National Oilwell Varco*, *Bentec*, *Pason*, *Canrig*, *ElectroProject*, and *HELB*, which have included:

(i) Different implementations of automatic drilling systems based on draw-works hoist drive speed and hook-load (WoB) control, either based on draw-works hoist brake control, main electrical drive control, and their combined use. Implementations suitable for directional drilling applications have also been discussed;

(ii) Torsional vibrations active damping systems based on the well-established *Soft Torque Rotary System*^{TM} (STRS) concept have been outlined, along with some recent R&D results, and the basic idea of traditional proportional-integral (PI) speed controller of the rotary drilling electrical drive as an equivalent implementation of mechanical passive vibration absorber has been discussed. A more recent *Z-Torque*^{TM} active damping concept proposed by *Shell* has also been presented and discussed.

(iii) A mud pump system pressure pulsation mitigation strategy currently offered by *Bentec* (*Soft Pump System*^{TM}) has been outlined with the main concept of individual pump synchronization and phase displacement coordination also being presented.

Along with these commercially available products for drilling system automation purposes, the energy efficiency improvement measures have also shown certain potential to oil/gas drilling and supporting enterprises. Hence, a literature review regarding the potential for oil drilling industries energy efficiency improvement has also been presented herein.

The related research and development (R&D) efforts stemming from the cooperation between the Croatian oil drilling businesses and the University of Zagreb have been presented, along with the results of representative field tests and extensive simulation studies. The presented overview has indicated that:

(i) Current commercially-available implementation of draw-works brake-based automatic drilling system (*HELB – Automatic Driller*^{TM}) is able to achieve favorable WoB control with consistent tool RoP, especially when compared to manual brake control. Based on simulation results, draw-works electrical drive control can offer a distinctive advantage over the current brake-based system;

(ii) *HELB Active Damping System – Soft Drive*^{TM}, featuring a PI speed controller tuning procedure aimed at the tool-side torsional vibration attenuation, and a proprietary back-spinning prevention algorithm have been successfully implemented in the field, and are currently commercially available;

(iii) Mud pump system pressure pulsation mitigation strategy is currently being intensively researched, and the preliminary simulation results show clear potential for pressure pulsation reduction;

(iv) Finally, the recent research in drilling rig AC microgrid hybridization has indicated that a notable fuel efficiency improvement of the diesel power-plant can be achieved (12% less fuel expended), compared to the conventionally operated power-plant. These results point out to a relatively short BESS return of investment period, along with associated CO_2 emissions reduction potentials.

Future work in oil drilling system R&D within the Croatian oil drilling related businesses is going to be directed towards further development and refinement of automatic drilling and torsional vibrations active damping systems, as well as laboratory testing and field implementation of mud pump coordination aimed at suppressing harmful mud pipeline pressure pulsations. A laboratory implementation of scaled-down oil drilling rig energy management system prototype is likely to be built, in preparation for the prospective development of energy management system aimed at diesel power-plant fuel efficiency improvement.

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6. REFERENCES

[1] Sorrell, S., Speirs, J., Bentley, R., Brandt, A., Miller, R.: *Global oil depletion: A review of the evidence,* Energy Policy, 38(2010)9, 5290-5295.

[2] Bardi, U.: *Peak Oil: The four stages of a new idea*, Energy, 34(2009)3, 323-326.

[3] Statoil, A.S.A.: *Statoil 2014 Sustainability report* (www.statoil.com/sustainability), Norway, 2015.

[4] British Petroleum PLC: *BP Sustainability Report 2014* (www.bp.com/sustainability), UK, 2015.

[5] Foss, B.: *Process Control in Conventional Oil and Gas Fields – Challenges and opportunities*, Control Engineering Practice, 20(2012)10, 1058-1064.

[6] Luo D., Zhao, X.: *Modeling the operating costs for petroleum exploration and development projects*, Energy, 40(2012)1, 189-195.

[7] Lyons, W. C., Plisga G. J. (ed.): *Standard Handbook of Petroleum & Natural Gas Engineering*, 2nd ed., Gulf Professional Publishing (imprint of Elsevier), Burlington, MA, USA, 2005.

[8] Wu, S., Li. J., Liu, L.: Modeling and Compound Control of Disk Brake Automatic Drilling System, Proceedings of 2nd International Conference on Computer Engineering and Technology, Volume 3, Chengdu, China, 2010, 45-49.

[9] Jansen, J.D., van den Steen, L.: *Active Damping of Self-Excited Torsional Vibrations in Oil Well Drillstrings*, Journal of Sound and Vibration, 179(1995)4, 647-668.

[10] Mihajlovic, N., Van Veggel, A.A., Van de Wouw, N., Nijmeijer, H.: *Analysis of friction-induced limit cycling in an experimental drill-string system*, ASME Journal of Dynamic Systems, Measurement and Control, 126(2004)4, 709-720.

[11] Pavković, D., Deur, J., Lisac, A.: *A Torque Estimator-based Control Strategy for Oil-Well Drill-string Torsional Vibrations Active Damping Including an Auto-tuning Algorithm*, Control Engineering Practice, 19(2011)8, 836–850.

[12] Dwars, S.: *Recent Advances in Soft Torque Rotary Systems*, Proceedings of the 3rd International Colloquium on Nonlinear Dynamics and Control of Deep Drilling Systems, Minneapolis, Minnesota, US, 2014, 29-44.

[13] White, S.: *Anatomy of the Mud Pump Pulse*, Upstream Pumping Solutions, Fall 2010.
[14] Bentec GmbH Drilling & Oilfield Systems: *Soft Pump*, Technical Data Sheet, Bad Bentheim, Germany, 2013. (www.bentec.com/equipment/electrical-drilling-rig-equipment/soft-pump-system/)
[15] Ray. J.: *Well Drilling Control System*, US Patent No. 6994172, 2006.
[16] Power, D. J., Glaser, G. P.: *Automatic Drilling System*, US Patent No. 7059427 B2, 2006.
[17] Zhao, Q., Wang, F., Wang, W., Deng, H.: *Adaptive Fuzzy Control Technology for Automatic Oil Drilling System*, Proc. of the IEEE International Conference on Automation and Logistics, Jinan, China, 2007, 2123 – 2127.
[18] National Oilwell Varco: *MotorDriller Dynamic Auto-Drill Function* (www.nov.com), 2014.
[19] Canudas-de-Wit, C., Rubio, F.R., Corchero, M.A.: *D-OSKIL: A New Mechanism for Controlling Stick-Slip Oscillations in Oil Well Drillstrings*, IEEE Transactions on Control Systems Technology, 16(2008)6, 1177 – 1191.
[20] Runia, J. D., Dwars, S., Stulmeier, I. P. J. M.: *A brief history of the Shell "Soft Torque Rotary System" and some recent case studies*, Proc. of SPE/IADC Drilling Conference, Amsterdam, Netherlands (SPE-163548-MS), 2013.
[21] Tucker, R.W., Wang, C.: *On the Effective Control of Torsional Vibrations of Drillstring Systems*, Journal of Sound and Vibration, 224(1999)1, 101-122.
[22] Abdulgalil, F., Siguerdidjane, H.: *PID based on sliding mode control for rotary drilling system*, Proceedings of EUROCON 2005 Conference, 2005, 262-265.
[23] Puebla, H., Alvarez-Ramirez, J.: *Suppression of Stick-Slip in Drillstrings: A Control Approach Based on Modeling Error Compensation*, Journal of Sound and Vibration, 310(2008)4-5, 881-901.
[24] Navarro-López, E.M., Licéaga-Castro E.: *Non-desired transitions and sliding-mode control of a multi-DOF mechanical system with stick-slip oscillations*, Chaos, Solitons & Fractals, 41(2009)4, 2035-2044.
[25] Serrarens, A.F.A., Van de Molengraft, M.J.G., Kok, J.J., van den Steen, L.: *H-infinity Control for Suppressing Stick-Slip in Oil Well Drillstrings*, IEEE Control Systems Magazine, 18(1998)2, 19-30.
[26] Karkoub, M., Zribi, M., Elchaar L., Lamont L: *Robust μ-synthesis controllers for suppressing stick-slip induced vibrations in oil well drill strings*, Multibody System Dynamics, 23(2010)2, 191-207.
[27] Mazzetti, M. J., Nekså, P., Walnum, H. T., Hemmingsen, A. K. T.: *Energy-Efficient Technologies for Reduction of Offshore CO_2 Emissions*, SPE Oil and Gas Facilities, 3(2014), (SPE paper No. 169811), 89- 96
[28] Baker-Hughes: *International Rig Counts* (phx.corporate-ir.net/phoenix.zhtml?c=79687&p=irol-rigcountsintl), November 2016.
[29] Kaiser, M. J., Snyder, B. F.: *The Offshore Drilling Industry and Rig Construction in the Gulf of Mexico*, Lecture Notes in Energy 8, Springer-Verlag, London, UK, 2013.
[30] National Oilwell Varco: *Wildcat ADS Automated Drilling System* (www.nov.com), 2009.
[31] Pason Co.: *The Pason AutoDriller – Optimal Drilling Control and Accuracy*, Application Note (www.pason.com/rig-site/automatic-driller/), 2016.
[32] Canrig Drilling Technology Ltd.: *DrillSmart Automatic Driller* (www.canrig.com), 2016.
[33] National Oilwell Varco: e-*Wildcat Draw-works Electronic Autodrilling System* (www.nov.com), 2014.
[34] Bentec GmbH Drilling & Oilfield Systems: *Bentec Feed-Off Control System (FOCS)* (www.bentec.com), 2016.
[35] Hofschroer, M.: *Automation aims for higher efficiency wells*, Drilling Contractor (2004) Sep./Oct.
[36] Rigserv International Ltd.: *SmartDrill 21 – Intelligent Automatic Drilling & Block Safety System*, Technical Description (www.rigserv.com), 2016.
[37] Jardine, S., Malone, D., Sheppard, M.: *Putting a Damper on Drilling's Bad Vibrations*, Oilfield Review, 6(1994)1, 15-20.
[38] Attar, F., Grauwmans, R., & Ikhajiagbe, O.: *Soft Torque Impact on Drilling Performance in Qatar*, International Petroleum Technology Conference, 2014.
[39] National Oilwell Varco: *NOV stick-slip prevention service effectively reduces downhole vibrations and smooths the downhole drilling environment on the Monterey Shale*, Press Release, 2016.
[40] Bentec GmbH Drilling & Oilfield Systems: *Soft Torque Rotary System - Saves costs by eliminating drill string stick-slip effects*, Technical Data Sheet, Jan. 2016.
[41] Canrig Drilling Technology Ltd.: *Drilling Performance Services* (www.canrig.com), 2016.
[42] ElectroProject Aandrijftechniek: *Electroproject Soft Torque (EPST)*, Technical Data Sheet (www.softtorque.com), 2016.
[43] National Oilwell Varco: *Mud Pumps - 14-P-220 Triplex Pumps*, Technical Marketing Sheet, 2016.
[44] Bentec GmbH Drilling & Oilfield Systems: *Soft Pump System*, Technical Data Sheet, Feb. 2016.

[45] Díaz-de-Baldasano, M. C., Mateos, F. J., Núñez-Rivas, L. R., Leo, T. J.: *Conceptual design of offshore platform supply vessel based on hybrid diesel generator-fuel cell power plant*, Applied Energy, 116(2014), 91-100.

[46] Craig, C., Islam, M.: *Integrated Power System Design for Offshore Energy Vessels and Deepwater Drilling Rigs*, IEEE Transactions on Industry Applications, 48(2012)4, 1251-1257.

[47] Dekka, A., Beig, A. R., Kanukollu, S., Al Rahis, M. S.: *Retrofitting of Harmonic Power Filters in Onshore Oil Drilling Rigs: Challenges and Solutions*, IEEE Transactions on Industry Applications, 50(2014)1, 142-154.

[48] Lujun, Z.: *An energy-saving oil drilling rig for recovering potential energy and decreasing motor power*, Energy Conversion and Management, 52(2011)1, 359-365.

[49] Mazzetti, M. J., Nekså, P., Walnum, H. T., Hemmingsen, A. K. T.: *Energy-Efficient Technologies for Reduction of Offshore* CO_2 *Emmissions*, SPE Oil and Gas Facilities, 3(2014)1, (SPE paper No. 169811). 89-96

[50] HELB Ltd.: *Power Supply and Automation – Solutions and services for offshore and onshore drilling rigs*, Technical Brochure, (www.helb.hr/oil-and-gas), 2016.

[51] Leonhard, W.: *Control of Electrical Drives*, Springer-Verlag, Berlin, Germany, 2001.

[52] BEI Sensors Co.: *HS45 Incremental Optical Encoder*, Data Sheet (www.beisensors.com), 2013.

[53] Naslin, P.: *Essentials of Optimal Control*, Illife Books Ltd., London, UK, 1968.

[54] Schröder, D., *ElektrischeAntriebe - Regelung von Antriebssystemen*, 3rd ed., Chap. 19, Springer-Verlag, Berlin, Germany, 2007.

[55] Karassik, I.J., Messina, J.P., Cooper, P., Heald, C.C.: *Pump Handbook*, 4th ed., The McGraw-Hill Companies, Inc., 2008.

[56] Pavković, D., Sedić, A., Guzović, Z.: *Oil Drilling Rig Diesel Power-plant Fuel Efficiency Improvement Potentials through Rule-Based Generator Scheduling and Utilization of Battery Energy Storage System*, Energy Conversion and Management, 121(2016), 194-211.

[57] Caterpillar Tractor Co.: *Caterpillar D399 Marine Generator Set* (marine.cat.com/cat-D399), 2015.

[58] Pavković, D., Lobrović, M., Hrgetić, M., Komljenović, A.: *A Design of Cascade Control System and Adaptive Load Compensator for Battery/Ultracapacitor Hybrid Energy Storage-based Direct Current Microgrid*, Energy Conversion and Management, 114(2016), 154-167.

[59] Fernão-Pires, V., Romero-Cadaval, E., Vinnikov, D., Roasto, I., Martins, J. F.: *Power converter interfaces for electrochemical energy storage systems – A review*, Energy Conversion and Management, 86(2014), 453-475.

[60] Pavković, D., Hoić, M., Deur, J., Petrić, J.: *Energy Storage Systems Sizing Study for a High-Altitude Wind Energy Application*, Energy, 76(2014), 91-103.

[61] International Renewable Energy Agency (IRENA): *Road Transport: The Cost of Renewable Solutions*, IRENA's Costing Study (www.irena.org/publications), 2013.

[62] GWL/Power Group: *SE100AHA Cell Specification* (www.ev-power.eu), 2015.

[63] Pavković, D., Komljenović, A., Hrgetić, M., Krznar, M.: *Experimental Characterization and Development of a SoC/SoH Estimator for a* $LiFePO_4$ *Battery Cell*, Proc. of IEEE EUROCON 2015, Salamanca, Spain, 2015, (397-402),

[64] www.ihs.com/products/oil-gas-drilling-rigs-offshore-day-rates.html